T&SD Technology & Solutions Division

Engine Research

Heavy-Duty Low Temperature Combustion Development Activities at Caterpillar®

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Parag Mehresh and David Milam – Caterpillar®

Glen Martin and Chuck Mueller - Sandia National Laboratories

Paul Bessonette – ExxonMobil®

DOE Contract DE-FC26-05NT42412
DOE Technology Development Manager: Roland Gravel
NETL Project Manager: Ralph Nine

DOE DEER Conference
Detroit, MI
Aug 12-16, 2007

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Goals and Objectives:

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- Develop technologies to enable a low emissions, high efficiency, production viable, low-temperature combustion engine system
  - 2010 on-highway/ Tier 4 off-road emissions compliant
  - 55% thermal efficiency (~30% carbon emissions reduction)
  - Increased customer value

- Objective of low temperature combustion development
  - Take advantage of a thermodynamically attractive combustion process
  - Eliminate need for NOx or PM aftertreatment

    → Reduced backpressure and lower cost

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Low Temperature Combustion Challenges from Gap Analysis

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Technology Gaps

Potential Technology Solutions

Gap Analysis
- Evaluate Production readiness
- Evaluate customer value
- Evaluate competing technologies

Production Viable Solution

- **Excessive HC/CO emissions**
- **High heat rejection**
  - Increased EGR requirements
  - Increased in-cylinder heat transfer with HCCI
- **Not meeting power density / rating capability targets**
  - High equivalence ratio at high BMEP → high soot emissions
  - Cylinder pressure and rise rate limits
  - Low load combustion stability/ignition
- **Robust combustion control**
  - Cylinder-to-cylinder variability
  - Ambient temperature and pressure changes
  - Transient operation

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Systems approach to low temperature combustion development

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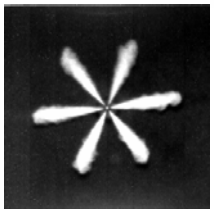
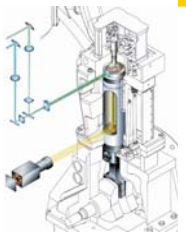
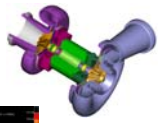
- Develop a fundamental understanding of low-temperature combustion process

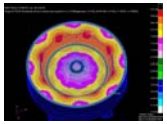



- Develop advanced technologies to enable low temperature combustion





- Collaborate with technology experts

Sandia National Laboratories

ExxonMobil Research and Engineering

IAV Inc. Automotive Engineering

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Optical Engine Testing with Sandia National Laboratories

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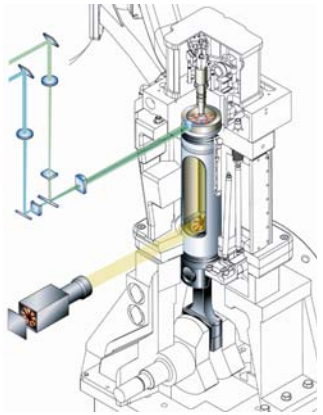
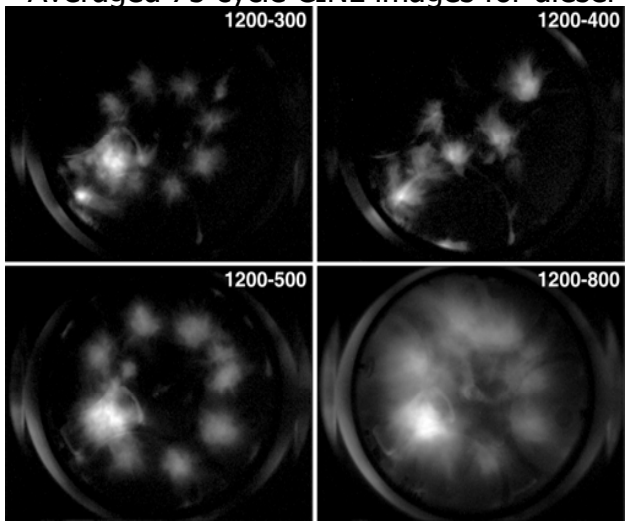
- Objectives:
  - Use optical diagnostics to improve fundamental understanding of in-cylinder processes and validate computational models
- Approach:
  - Work completed by Glen Martin and Chuck Mueller
  - Natural luminosity imaging of combustion
    - Shows spatial and temporal evolution of soot incandescence
    - High signal indicative of high soot concentration and/or temperature
- Results:
  - Previous natural luminosity results showed a relationship between smoke emissions and the intensity of the pool fires at the locations of liquid fuel impingement on piston surface



Schematic of SCORE configured for laser-sheet imaging.

Averaged 75 cycle CINL images for diesel



AVL Max Target of 0.1

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Optical Engine Testing with Sandia National Laboratories

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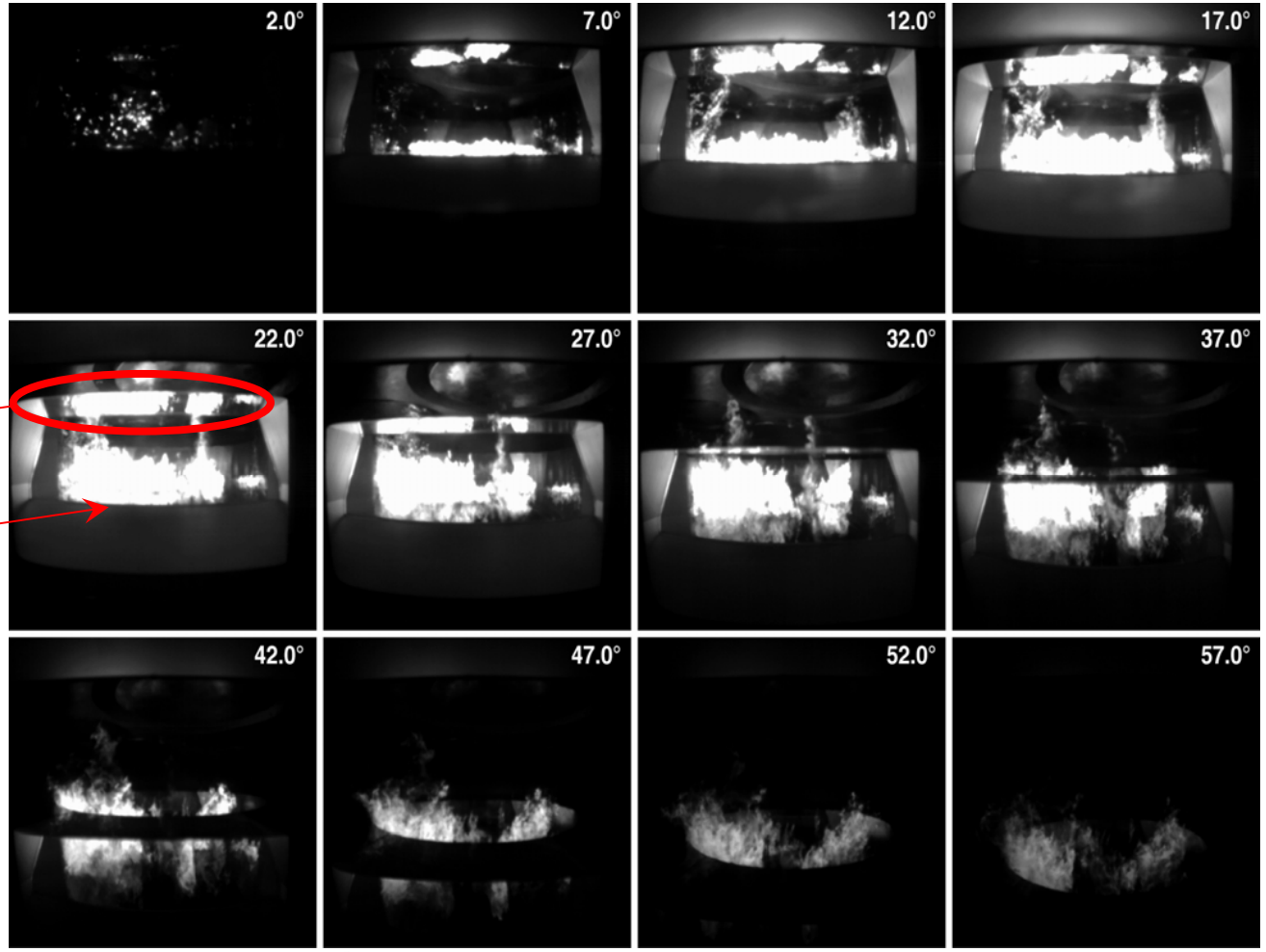
- Results:
  - Confirmation of pool fires on surface of piston bowl



- Conclusion:
  - Liquid fuel impingement on the piston bowl is a significant factor for soot emissions

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Advanced Fuel Systems Development

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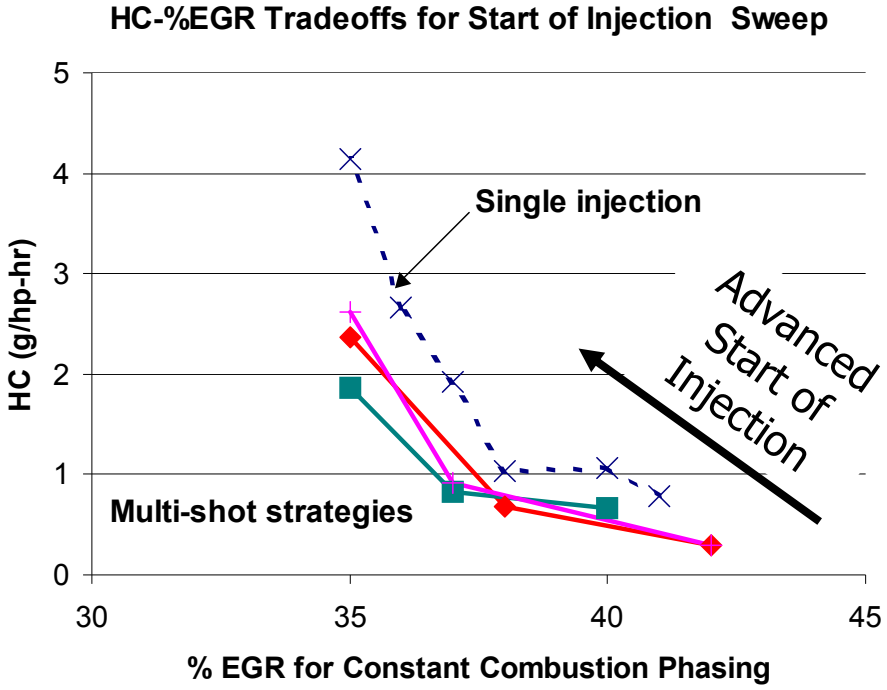
- Objective:
  - Investigate fuel injection strategy as a means to affect mixture preparation and reduce liquid fuel impingement
- Approach:
  - Swept start of injection timing and adjusted EGR to achieve constant combustion phasing
  - Varied injection strategy
    - # of shots (up to 4), injection spacing and fuel apportionment
- Results:
  - Multiple injection strategies improved the EGR-HC tradeoff

  → Increased homogeneity, less liquid fuel impingement



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Advanced Fuel Systems Development

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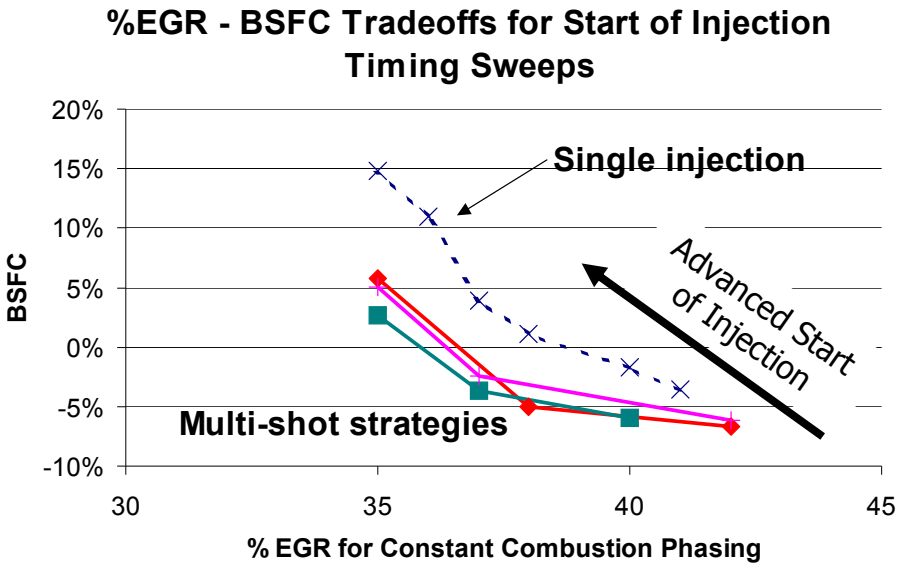
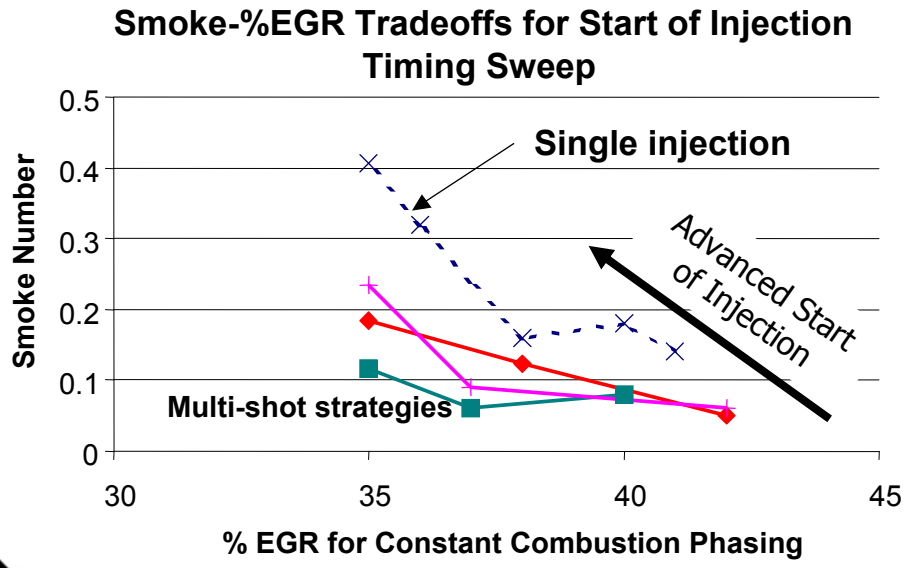
- Results:
  - Improved BSFC with multiple injections
    - Reduced fuel dilution of engine oil
    - Improved carbon balance (carbon in compared to carbon out)

    → Reduced liquid fuel impingement on liner
  - Reduced smoke emissions with multiple injection

    → Reduced liquid fuel impingement on piston surface

    → More homogeneous mixture preparation
- Conclusion:
  - Multiple injections are beneficial for HCCI mixture preparation and emissions





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Fuel Property Investigation

in collaboration with ExxonMobil®

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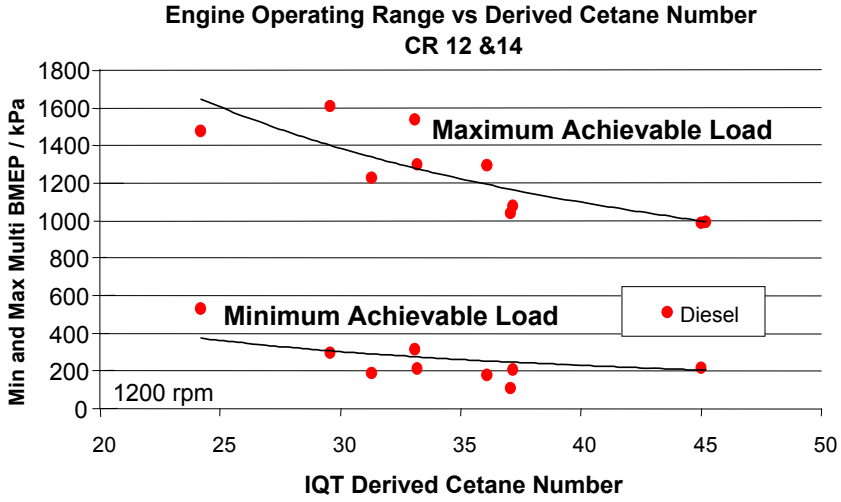
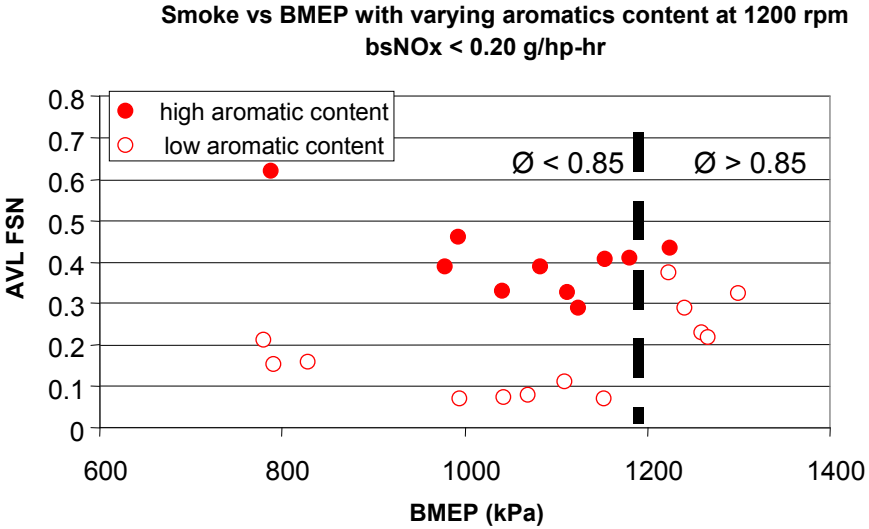
- Objective:
  - Tailor fuel properties to engine characteristics and/or engine operating conditions for low temp combustion
  - Establish impact of fuel properties on emissions with low temperature combustion
- Approach:
  - Tested diesel fuels with varying…
    - cetane number
    - aromatic/ iso-paraffin composition but equal cetane number
- Results:
  - Established relationship between engine characteristics, diesel fuel cetane number and engine load capability
  - Demonstrated modest benefit of lower aromatic content fuels in reducing soot emissions





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HCCI with Variable Compression Ratio (VCR)

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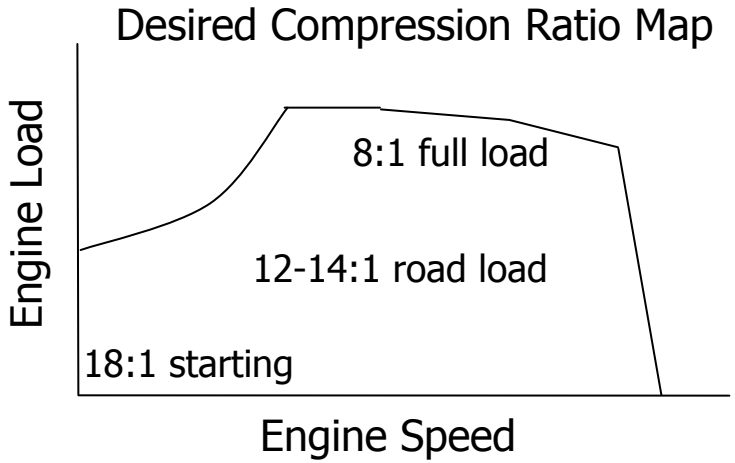
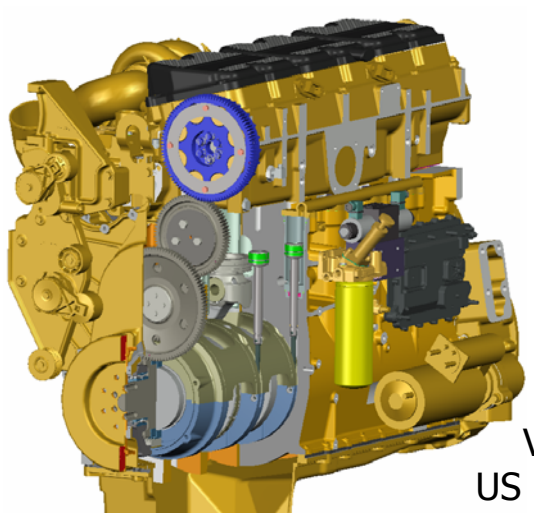
- Objective:
  - Demonstrate functional viability of eccentric crankshaft VCR mechanism
  - Quantify benefits of VCR engine relative to load capability, fuel consumption and combustion control robustness



- Approach:
  - Successfully designed, built and tested an eccentric crankshaft variable compression ratio engine
  - Used engine to demonstrate benefits of variable compression ratio and investigate control strategies



VCR
US Patent
Application
2006/0112911

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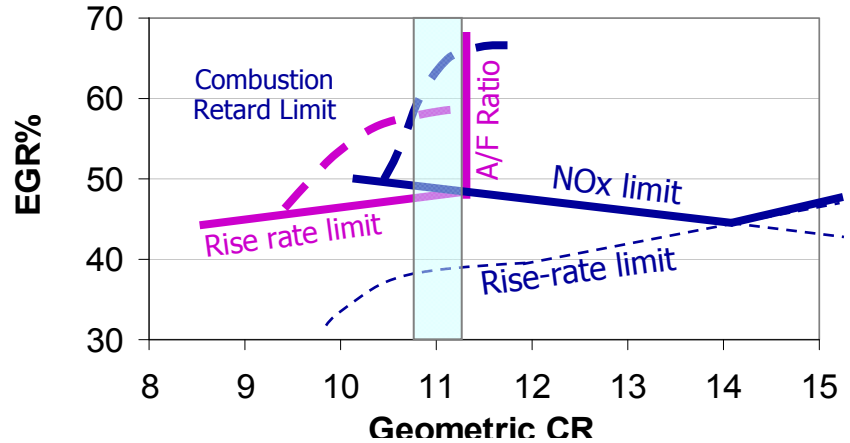
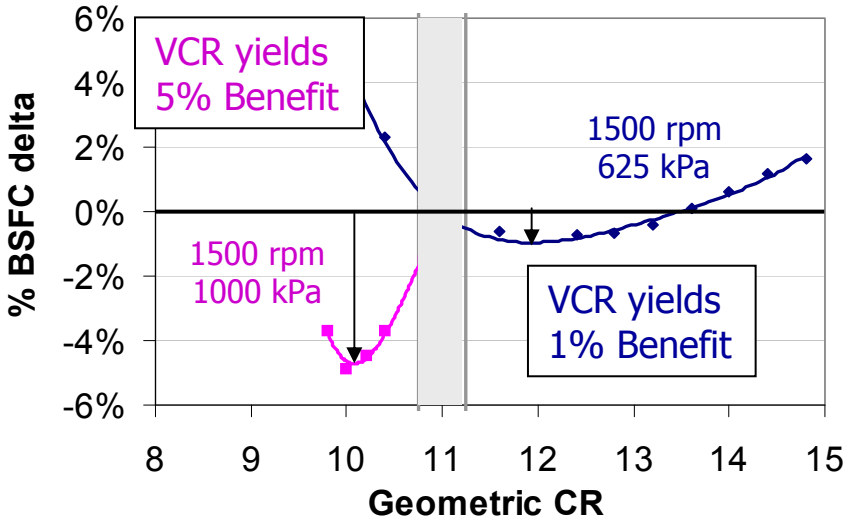
HCCI with Variable Compression Ratio (VCR)

T&SD Technology & Solutions Division

- Results:
  - A fixed compression ratio must be chosen that allows robust operation at all load conditions
    - Limited load range
    - Sacrifice fuel consumption
  - With variable compression ratio, optimum BSFC can be attained without limiting operating range
- Conclusion:
  - VCR is an effective technology for increasing engine operating range and achieving optimal thermal efficiency

Fixed Compression Ratio Compromise





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Summary

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- Caterpillar® continues to explore low temperature combustion as a high efficiency, low emissions engine technology
- Optical engine experiments provided valuable insight into combustion fundamentals, such as the relationship between liquid fuel impingement and soot emissions
- Multiple injections improved mixture preparation and thus lowered EGR requirements while reducing HC and smoke emissions
- Fuel property investigations provided a relationship between diesel fuel cetane number and engine load capability and a relationship between aromatic content and smoke emissions.
- Variable compression ratio engine allowed the engine operating range to be robustly expanded and BSFC to be optimized.

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